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"Picosecond Soft-X-ray studies of Dense Plasma Regimes"

Progress Report (April 1 2006- March 31 2007)

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Abstract

The goal of this project is to investigate and characterize high-density converging plasma configurations using new soft x-ray laser based interferometric techniques. The results are used to verify and validate multi-dimensional hydrodynamic codes in plasma regimes which densities and size exceed those that can be probed with optical laser beams. The dynamics of converging plasmas created by laser irradiation of half-hohlraum cylindrical cavities targets was probed using a compact 46.9 nm soft x-ray laser. The results were used for comparison with extensive simulations conducted with the multi-dimensional hydrodynamic code HYDRA. As part of this study we have also investigated plasma regimes in which the index of refraction of the plasmas can not be defined solely based on the contribution of free electron, as is usually assumed for multiply ionized plasmas. Our results demonstrate the existence of plasma regimes in which the contribution of bound electrons from ions dominates the refractive index at soft x-ray wavelengths. We are also working in extending plasma interferometry to the sub 10 nm wavelength range. In the process we are advancing soft x-ray laser plasma diagnostics techniques to allow the measurement of large-scale, high-density plasmas with picosecond temporal resolution and micrometer spatial resolution, laying the foundations for future advanced diagnostics at high energy density DOE facilities.

Introduction

Soft x-ray laser interferometry measurements of dense converging plasmas created irradiating semi-cylindrical cavities were conducted using a Mach-Zehnder soft x-ray interferometer and a capillary discharge soft x-ray laser developed at Colorado State University.

The research completed during the first year of the project includes:

1. Soft x-ray interferometry measurements of the electron density evolution of converging plasmas created by laser irradiation in half-hohlraums.
2. Comparison of the density maps obtained from the soft x-ray interferometry measurements with extensive simulations performed with the multi-dimensional hydrodynamic code HYDRA.
3. Observation of multiply ionized Carbon, Silver and Tin plasmas with index of refraction greater than one at the probe wavelength of 46.9 nm. The results expand the observation of a plasma with index greater than one than we made during the interferometry studies of laser-created Al plasmas at a 14.7 nm probe wavelength.
4. We have designed an interferometer for extending the soft x-ray laser interferometry technique to the 7 nm spectral region for probing plasmas of increased density and size.

In the first set of experiments, the evolution of dense aluminum and carbon plasmas produced by laser irradiation of 500 μm diameter semi-cylindrical targets was studied using soft x-ray laser interferometry. Plasmas created heating the cavity walls with 120 picosecond duration optical laser pulses of $\sim 1\times10^{12}$ W cm^{-2} peak intensity were observed to expand and collide on axis to form a localized high density plasma region. Electron density maps were measured using a 46.9 nm wavelength tabletop capillary discharge soft x-ray laser probe in combination with an amplitude division interferometer based on diffraction gratings. The measurements show that the plasma density on axis exceeds 1×10^{20} cm^{-3}. The electron density profiles were compared with simulations conducted using the hydrodynamic code HYDRA, which show that the abrupt density increase near the axis is dominantly caused by the convergence of plasma generated at the bottom of the groove during laser irradiation.

In a second set of experiments we extended the results obtained previously that unveiled the importance of bound electron contribution to the index of refraction in multiply-ionized plasmas. This observation resulted from the measurement of anomalous fringe shifts in soft x-ray laser interferograms of Al laser-created plasmas at 14.7 nm probe wavelength [1]. It is concluded that the usually neglected bound electron contribution to the index of refraction of multiply ionized plasmas can affect the propagation of soft x-ray radiation in plasmas and the interferometric diagnostics of plasmas for many elements at many wavelengths. The 46.9 nm plasma interferometry experiments done with different materials (Carbon, Tin and Silver) confirmed the wide spread nature of this phenomenon.

I. Study of converging plasmas created in half-hohlraums

We have used soft x-ray plasma interferometry to study converging plasmas created by laser irradiation of semi-cylindrical targets. The results were compared and analyzed with extensive simulations performed with the hydrodynamics code HYDRA developed at Lawrence Livermore National Laboratory. Laser heating of these half-hohlraum cylindrical cavities creates pressure gradients near the walls that radially accelerate the plasma towards the axis of the cavity, where it interacts colliding with itself. This interaction can range from stagnation to extended interpenetration. Comparison of direct measurements of the electron density evolution with code simulations can contribute to a better understanding of the plasma dynamics and serve to benchmark these complex codes and determine their regimes of validity. The measurements also reveal plasma regimes in which the standard approximation to computing the index of refraction of multiply ionized plasmas based only in the contribution of free electrons is not valid, and in which the role of bound electrons is dominant [1-3].

A soft x-ray laser interferometer operating at a wavelength of 46.9 nm was used to study dense converging plasmas produced by laser irradiation of 500 μm diameter semi-cylindrical targets made of different materials (C, Al, Cu, Mo, Ag, Sn). The targets were irradiated with 120 ps duration optical laser pulses at intensities of $\sim 1\times10^{12}$ W cm^{-2}. The density maps obtained from these interferograms describe the radial expansion of the plasma off the target walls towards the axis of the cavity. The plasma is seen to converge in a focal region, creating a concentrated plasma region where the electron density build-up is measured to exceed 1×10^{20} cm^{-3}.

A sequence of interferograms corresponding to carbon plasmas obtained by irradiation of semi-cylindrical targets, are shown in figure 1. Each interferogram corresponds to a different time measured with respect to the arrival of the 600 mJ heating pulse onto the target surface. The first interferogram of the sequence was acquired at the time of the peak of the 120 ps heating pulse. Plasma absorption and fringe shifts are present in the region within ~50 μm of the target surface, indicating the early stage of the plasma expansion. The frame at 1.3 ns indicates that the plasma has already converged on axis and a fast density build-up is under way near the axis of the cavity. At 2 ns after the irradiation significant shifts of the fringes are observed in an oval shaped region near the axis, indicating the formation of a strongly pinched plasma. At 2.6 ns the fringes in this location remain highly perturbed, and absorption of the probe beam is observed near the surface of the target. The subsequent frame, at 5.0 ns, shows a significant decrease in the number of fringe shifts near the axis. The shifting continues to decrease with time until ~10 ns, at which the fringe visibility is lost due to significant absorption of the probe beam. The electron density maps resulting from the carbon plasma interferograms are shown in figure 2. The peak electron density is observed to occur at ~2.6 ns. Afterwards the density in this region is observed to decrease.

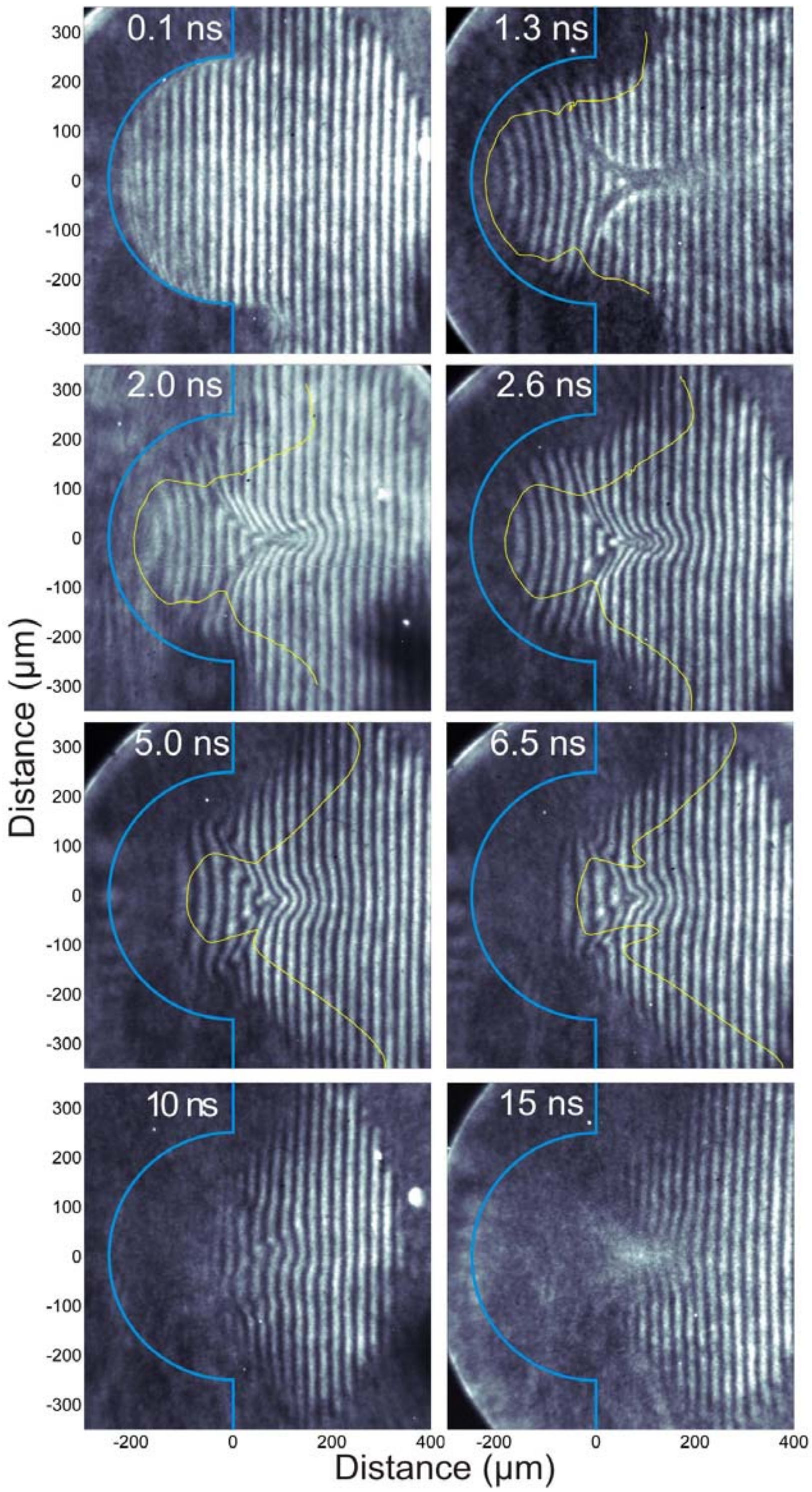

FIG. 1. Sequence of soft x-ray laser interferograms describing the evolution of carbon plasmas created by irradiating a half-hohlraum cylindrical cavity. The free electron approximation to the index of refraction is computed to be valid in the region to the right of the white line.

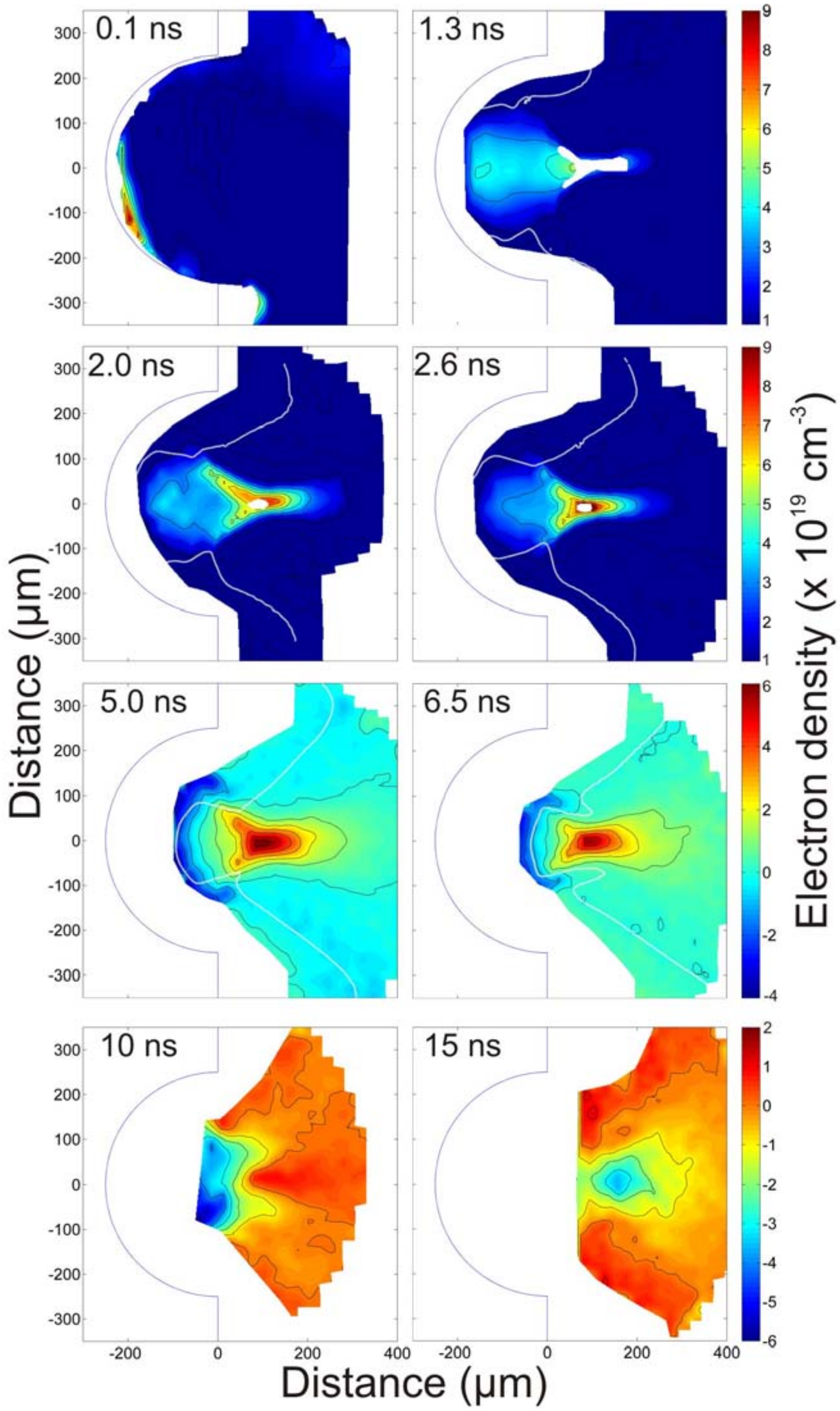

FIG. 2. Measured carbon electron density maps corresponding to the interferograms shown in figure 1. The free electron approximation to the index of refraction is computed to be valid in the region to the right of the white line.

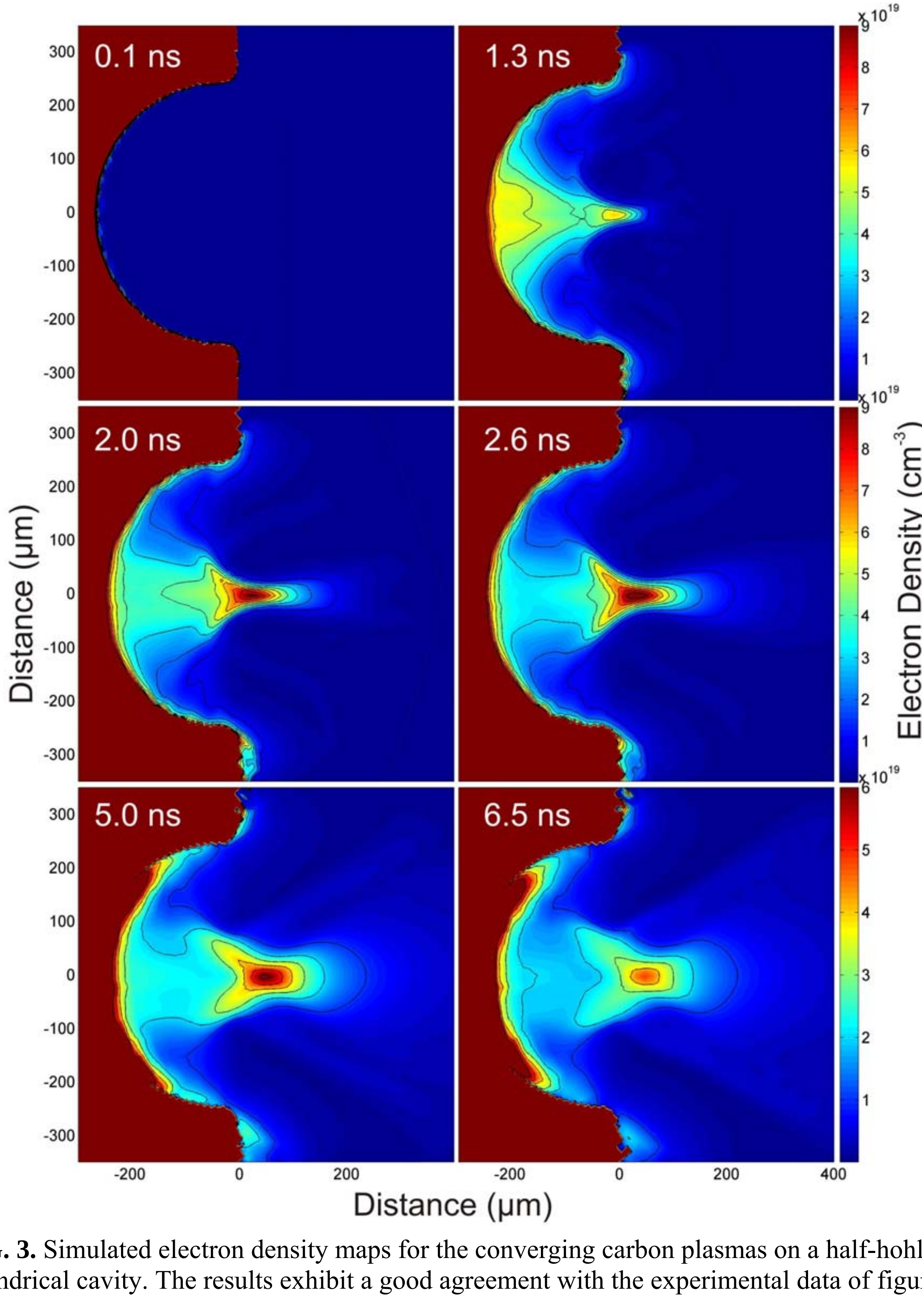

FIG. 3. Simulated electron density maps for the converging carbon plasmas on a half-hohlraum cylindrical cavity. The results exhibit a good agreement with the experimental data of figure 2.

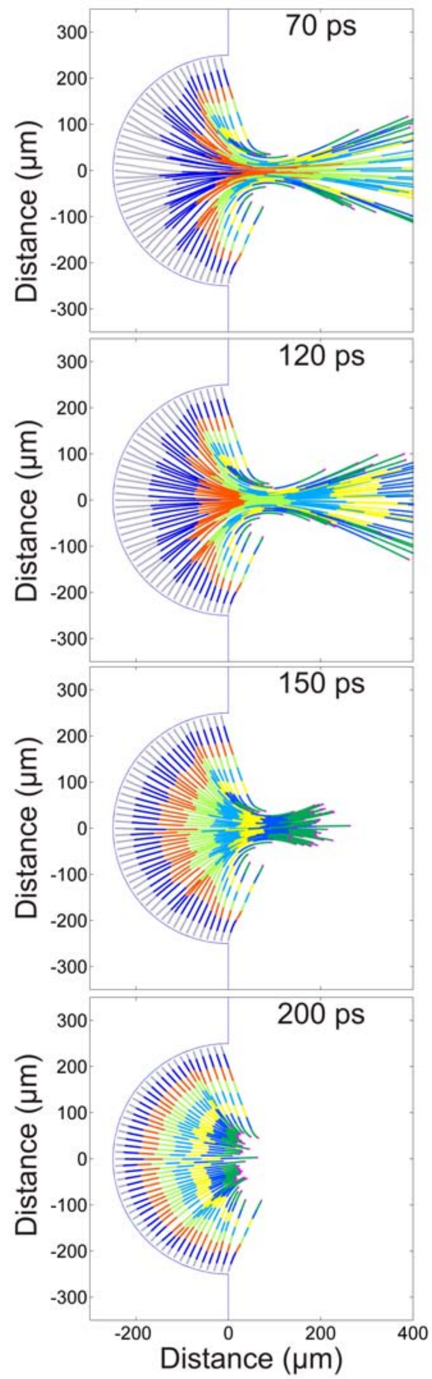

FIG. 4. Plots revealing 4s of the evolution of the trajectory corresponding to tracer particles leaving the semi-cylindrical target surface at four different time delays with respect to the beginning of the laser heating pulse. Alternating colors are used to represent time periods of 500ps. This plot reveals the convergence of plasma from a region located at the back of the half-hohlraum towards the axis.

The combination of the interferometry results of Fig.2 with 2-dimensional simulations HYDRA simulation results of Fig.3. enable the construction of a picture of the expansion and evolution of the plasmas. The simulations are in good agreement with the experiment. Such agreement is possible because the amount in this case the plasma is highly collisional and degree of plasma interpenetration is negligible. To better determine the relative contributions of the different regions of the wall to the plasma build-up in the focal region, tracer particle trajectories were computed. HYDRA was used to calculate vector fields at 10 ps intervals which were then used to define the trajectory of a set of tracer particles uniformly spaced along the curved surface of the target. Figure 4 shows the trajectory of particles ablated at times of 70, 120, 150 and 200 ps with respect to the arrival of the heating pulse. Each frame follows the tracer particles from the time they leave the surface (the dark blue color) up to 4 ns in the evolution (the yellow color). Each alternating color illustrates the trajectories over an elapsed time of 500 ps. The first particles to leave the target surface expand into vacuum accelerated outward by the increasing pressure gradients. The converging plasma emanating from within the 74 degree central region of the target at the time of the peak of the irradiation (70 ps frame) reaches the focus region in about 1.5 ns, causing an abrupt increase in the plasma density. Plasma leaving this region of the target at the end of the pulse (120 ps frame) arrives to the focus region at 2ns contributing significantly to the density build-up. In contrast, the tracer particles that start the evolution at target surface locations irradiated by a reduced intensity (larger angles) are noticeably slower and reach the focal region significantly later, near the end of the 4 ns evolution. Plasma radiation continues to ablate the target after the termination of the heating laser pulse. The trajectory plots that follow the particles which leave the target after the termination of the irradiation pulse (i.e. 150 and 200 ps frames) show this plasma moves significantly slower as a result of the colder temperature near the walls. Furthermore, plasma leaving the surface of the target at 200 ps doesn't reach the focal region where a plasma build-up occurs during the first 4 ns of the evolution. At this time all the tracer particles leave the target surface with similar velocity, irrespective of their position on the target surface. The density increase in the focal region is therefore dominantly formed by the convergence of plasma created at the bottom of the groove during the laser irradiation with additional contributions from plasma originating from the steeper wall of the cavity that arrives later and collides with little interpenetration.

In summary, due to the uneven heating of the target a hotter plasma is created at the bottom of the groove. This hotter plasma expands faster reaching the axis of the groove first, where it converges and forms the dense plasma focus. This faster and hotter plasma is followed by the arrival of successively colder and slower plasma created by plasma radiation-induced ablation of the target after the termination of the laser pulse. The simulations show that the plasma collision in the focal region redirects the velocity narrowing the stream of plasma that leaves the cavity. Collisions in the plasma focus region do not significantly increase the degree of ionization of the plasma. The plasma build-up occurring slightly off axis of the groove axis is instead mainly the result of the convergence of the plasma in a small region. The code simulations were also used to compute the degree of ionization of the plasma, which plays a role in determining the region of validity of the free electron approximation to the index of refraction of the plasma, and consequently the region of validity of the density maps obtained from the interferograms using this approximation. The results also illustrate that the combination of soft x-ray laser interferometry with 2-dimensional hydrodynamic simulations is a powerful tool to study the dynamics of dense plasmas.

II. Observation of multiply ionized plasma with index of refraction greater than one

For decades the analysis of interferometry experiments have relied on the approximation that the index of refraction in plasmas is due solely to the free electrons. This general assumption makes the index of refraction always less than one. However, recent soft x-ray laser interferometry experiments with Aluminum plasmas at wavelengths of 14.7 nm and 13.9 nm have shown fringes that bend the opposite direction than would be expected when using this approximation. Analysis of the data demonstrated that this effect is due to bound electrons that contribute significantly to the index of refraction of multiply ionized plasmas, and that this should be encountered in other plasmas at different wavelengths. We have now obtained new results in Carbon, Silver and Tin plasmas at 46.9 nm probe wavelength that clearly show the presence of plasma regions with an index of refraction greater than one. Computations suggest that in this case the phenomenon is due to the dominant contribution of bound electrons from doubly ionized ions to the index of refraction. A significant result of these studies with direct implications to the diagnostics of dense plasmas is clear experimental evidence showing that the contribution of bound electrons can dominate the index of refraction of laser-created plasmas at soft x-ray wavelengths.

The traditional formula that assumes only free electron contribution to the index of refraction of a plasma is n = (1 – Nelec / Ncrit)^1/2 where Nelec is the electron density of the plasma and Ncrit is the plasma critical density. At wavelength λ, Ncrit = π / (r0 λ^2) where r0 is the classical electron radius, 2.818 x 10^-13 cm. In typical experiments the electron density is much less than the critical density so the expression above can be approximated by n = 1 – (Nelec / 2Ncrit). For a plasma of length L the number of fringe shifts observed in an interferometer equals:

$$N_f = \frac{1}{\lambda}\int_0^L (1-n)\cdot dl$$

For the case of a uniform plasma along the direction of propagation of the probe beam, the above formula simplifies to N_f=(1 – n) L/λ. Substituting the approximation described above for the index of refraction, the number of fringe shifts N_f equals (Nelec L) / (2 λ Ncrit). To obtain electron density information from the interferogram, the fringe shifts are measured and then converted to electron density using the above approximations. Because the index of refraction is assumed always smaller than one, the fringes should always shift in one direction, determined by the geometry of the interferometer. From the anomalous fringe shift results in the interferometry experiments [1, 4] of the Al plasmas, it is clear that these assumptions used to analyze the VUV to soft x-ray interferometry are not always valid and that the bound electron contribution have to be taken into account in some cases.

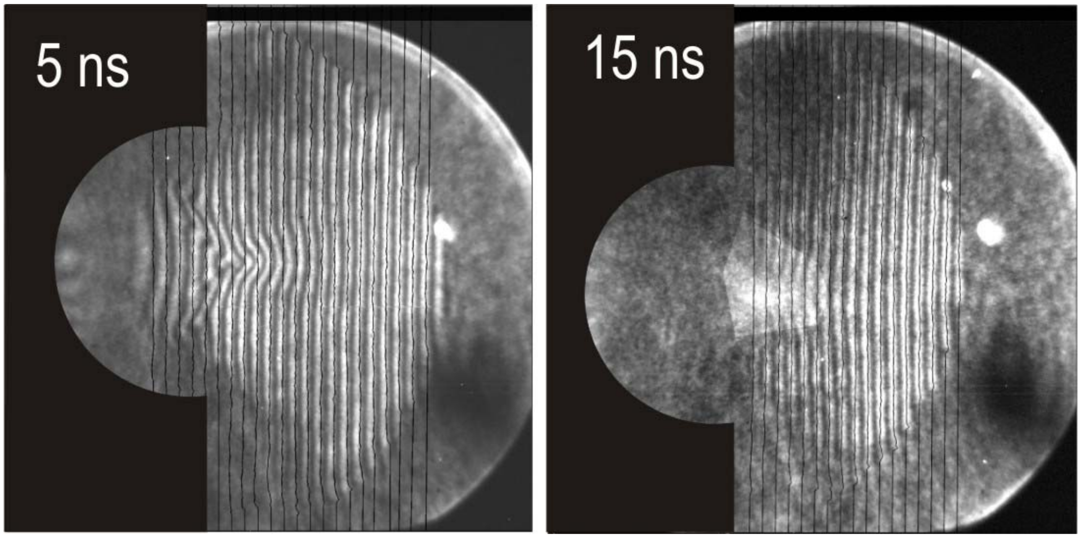

FIG. 5. Soft x-ray laser interferograms corresponding to two different times of the evolution of Carbon plasmas created in a semi-cylindrical cavity. Regions with fringes shifting to the left exemplify negative fringe shifts due to the dominant contribution of bound electrons to the index of refraction, that in those locations has values greater than one.

We have explored different plasmas to identify conditions in which the bound electron contribution is important. Aided by computer calculations and confirmed experimentally, we found that at a wavelength of 46.9 nm lowly ionized Carbon, Silver and Tin plasmas have an index of refraction greater than one [2, 3]. The computer calculations suggest that the main contributors to the index of refraction are the bound electrons of doubly ionized atoms.

The plasmas studied were generated by irradiating a 1 mm long, 500 μm in diameter semi-cylindrical 99.99% pure Carbon target with an 800 nm wavelength laser pulse of 120 ps (FWHM) duration and up to 0.6 J of energy from a Ti:Sapphire laser. A line focus ~1.7 mm long and 300 μm wide, resulting in an irradiance of $\sim 1 \times 10^{12}$ W cm^{-2} was formed at the target plane using the combination of a 7 meter focal length spherical lens and a variable cylindrical lens used to adjust the beam astigmatism. The line focus shape and intensity at the target plane were monitored on every shot by imaging the reflection off a 4 % beam splitter onto a CCD camera. This target geometry combined with the relatively wide line focus irradiation generates a hot dense plasma on the axis of the cavity that when it cools down remains dense enough to produce significant fringe shifts.

Figure 5 show interferograms corresponding to two different times during the evolution of Carbon plasmas. The 5 ns frame shows interference fringes with maximum shifts on axis due to the convergence of the plasma produced by irradiating the walls of the semi-cylindrical target. The probe beam is strongly absorbed close to the target surface due to the presence of a large density of lowly charged ions. These ions have ionization potentials less than the 26.44 eV photon energy of the Ar soft X-ray laser. It is noticeable that the fringes closer to the target, at the bottom of the semi-cylindrical groove, shift to the left of the reference fringes (identified by the black lines over-imposed on the image), which imply that the index of refraction is greater than one. Later in time, in the 15 ns frame in Fig. 5 no significant fringe shifts are observed except near the semicylinder's axis and these fringes all bend toward the left of the reference fringes. The region where the probe beam is absorbed is now larger and completely fills the target cavity. The region with anomalous fringe shifts is always close to the region with higher absorption, suggesting that the presence of low ionized atoms is the cause of this anomalous index of refraction.

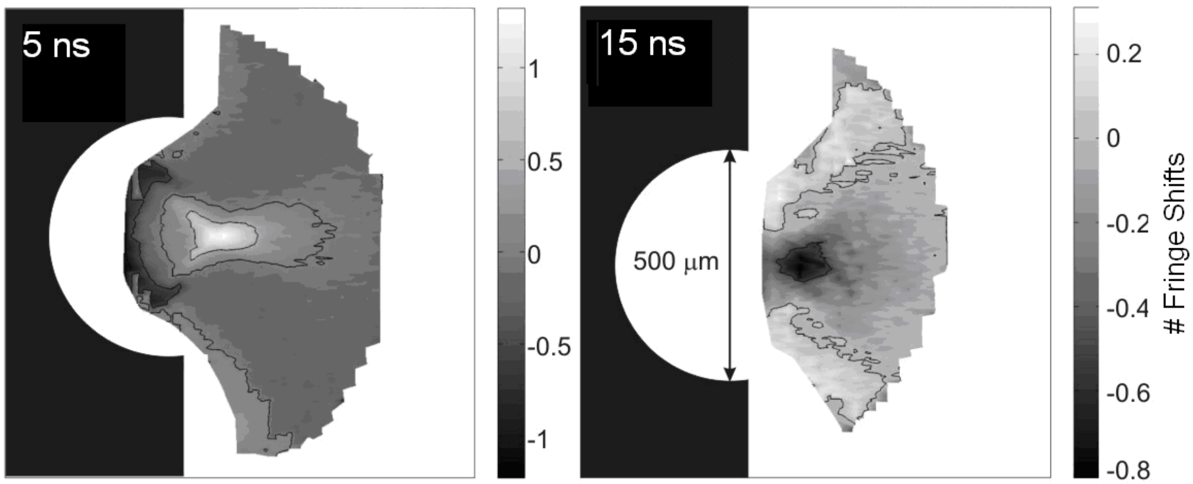

FIG. 6. Two-dimensional maps of the number of fringe shifts observed in the soft x-ray interferograms of the carbon plasmas shown Figure 1. Regions of negative fringe shifts corresponding to index of refraction greater than one are observed.

The 5 ns frame shows that at the axis of the cylindrical groove the plasma produces approximately 1 fringe shift, which would correspond to ~5×10^{19} cm^{-3} if only free electrons contributed to the index of refraction. We also observe that close to the absorption region, inside the groove and closer to the target, the plasma produces approximately one negative fringe shift, indicating an index of refraction greater than one. Later in time, the 15 ns frame shows very little fringe shifts overall except on the axial region that previously had the highest density. In this case almost one entire fringe shift is observed (–0.8 fringes).

To enable us to calculate the index of refraction for any plasma at any wavelength we used a modified version of the INFERNO average atom code. The INFERNO code [5] has been used for many years to calculate the ionization conditions and absorption spectrum of plasmas under a wide variety of conditions. We used a non-relativistic version of INFERNO to calculate bound and continuum orbitals and the corresponding self-consistent potential. The imaginary part of the complex dielectric function is proportional to the conductivity. The real part of the dielectric function can be found from its imaginary part using a Kramers-Kronig dispersion relation. The details of the Kubo-Greenwood formula applied to the average-atom model are described in [6]. For modeling purposes, we choose a Carbon plasma with an ion density of 10^{20} cm^{-3}. By varying the temperature of the plasma through the values 3, 6, 10 and 30 eV we can find the conditions where the Carbon plasma's mean ionization would be Z*=0.96, 1.97, 2.92, and 3.95. The ionization potentials of Neutral Carbon, C^{1+}, C^{2+}, C^{3+} and C^{4+} are 11.26 eV, 24.38 eV, 47.89 eV, 64.49eV and

392 eV respectively. The results of the calculations are plotted in figure 3. We use experimental energy level data to benchmark a point in the curve and shift the calculated curve accordingly.

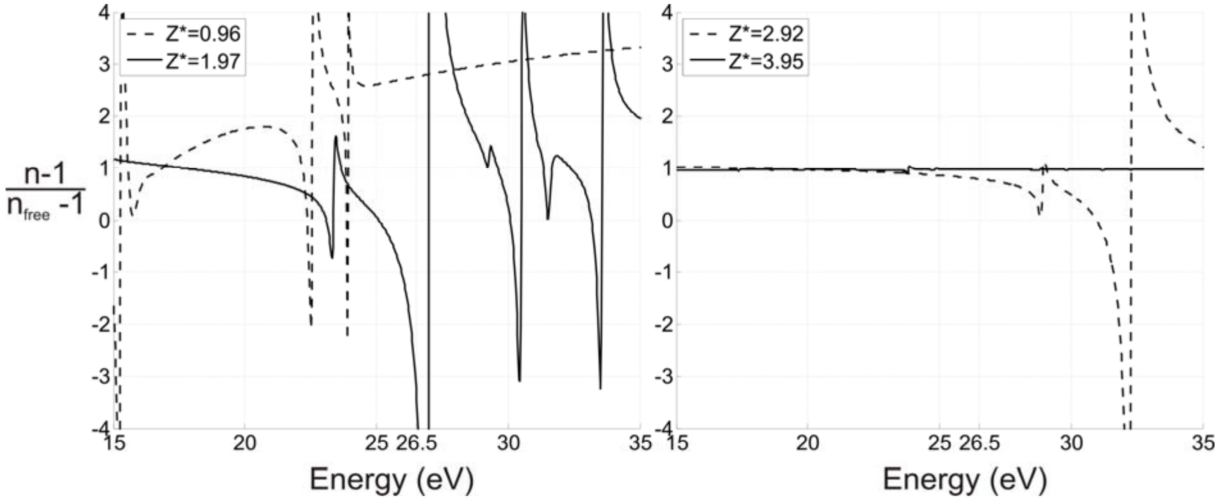

FIG. 7. Results from calculations of the index of refraction of carbon plasmas of different degree of ionization for a range of probe beam photon energies .

The ratio of n-1 over n_{free}-1, plotted in Fig. 3, gives an estimate of how far the calculated index of refraction is from the free electron approximation. When the ratio is larger than one the free and bound electrons are contributing with the same sign to the index of refraction. The calculated ratio is larger than one for singly ionized carbon, but this contribution does not show in the soft x-ray laser interferograms since the absorption edge is at 24.4 eV and photoionization strongly attenuates the beam in any region in which the density of singly ionized ions is large. The region close to the target probably has a large population of neutral and singly ionized carbon atoms. For doubly ionized carbon, there is a significant amount of structure with the ratio going negative for several energy intervals, in particular close to the 26.5 eV region. For triply and 4 times ionized atoms we see the ratio is approaching 1 with a strong structure near 30 eV for triply ionized, but without a major contribution from the bound electrons at 26.5 eV. All this suggests that in these experiments the observed anomalous fringe shifts are due to the dominant contribution of bound electrons from doubly ionized carbon ions to the index of refraction. This underscores the importance of having spectroscopic experimental data together with calculations that predict the index of refraction when performing interferometric diagnostics of plasmas.

Calculations using the average atom code predicted that Silver and Tin double ionized ions should also contribute significantly to the index of refraction at 46.9 nm probe wavelength. We performed plasma interferometry experiments with these materials. The same semi cylindrical geometry was used with similar irradiation conditions to generate the plasma as those used for the Carbon experiments. Figures 4 and 5 show interferograms taken early and late in the evolution of Tin and Silver plasmas, respectively. The early images show that the fringes on the axis of the semi-cylindrical cavity bend away from the target, indicating an index of refraction less than one. The plasma there is very dense and concentrated. Late in time, after the plasma has evolved for over 30 ns, the fringes on the axis of the cavity bend to the left of the reference fringes (drawn in black on the figure) indicating a plasma with an index of refraction greater than one. The average atom calculations predicted that the main contribution to the index of refraction, in this case, is due to doubly ionized atoms for both elements.

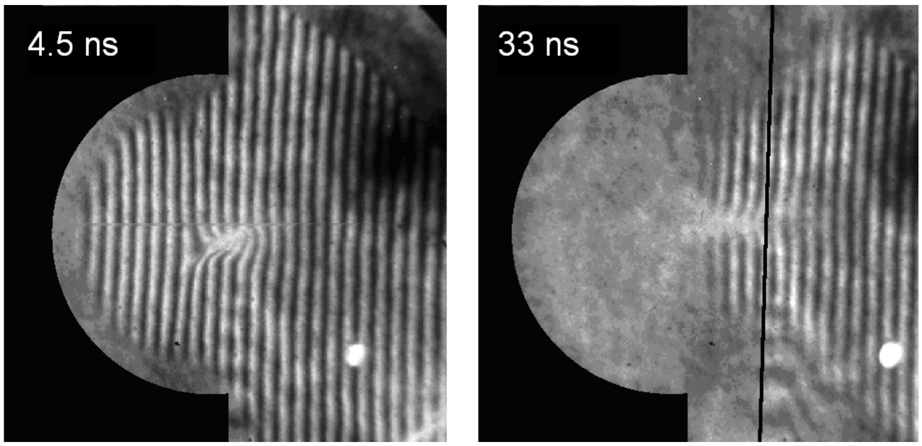

FIG. 8. Soft x-ray laser interferograms of tin plasmas taken under similar conditions as those of Fig. 1 . Late in the evolution the fringes are observed to bend to the left of the reference fringes indicating the presence of a region with an index of refraction greater than one.

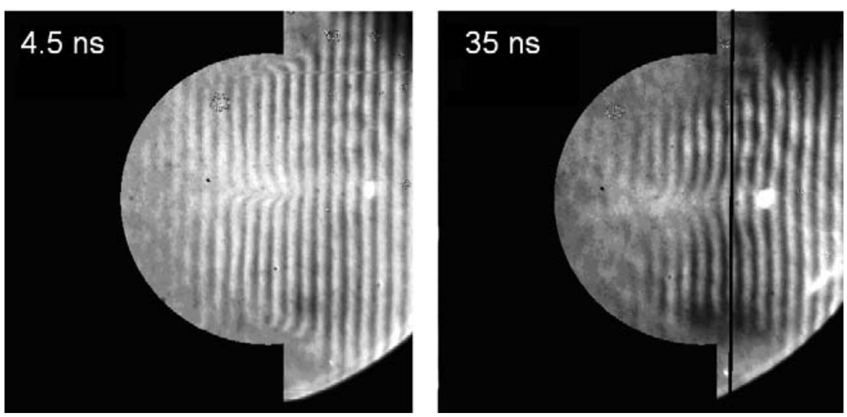

FIG. 9. Interferograms of silver plasmas taken under similar conditions as those of Fig. 5 Late in the evolution, the fringes bend to the left of the reference fringes indicating an index of refraction greater than one.

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Publications resulting from SSAA Grant support

I. Peer Review Journal Papers. (September 2005 –March 2007)

1. J. Filevich, J.J. Rocca, M.C. Marconi, S.J. Moon, J. Nilsen, J.H. Scofield, J. Dunn, R.F. Smith, R. Keenan, J.R. Hunter, V.N. Shlyaptsev, "Observation of a multiply ionized plasma with index of refraction greater than one", Physical Review Letters 94, 035005, (2005).
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II. Conference Proceedings and Abstracts (September 2005 – March 2007)

1. J. Grava, M. Purvis, J. Filevich, M. C. Marconi, J. J. Rocca, J. Dunn, S. J. Moon, R. F. Smith, J. Nilsen, and V. N. Shlyaptsev, "Soft x-ray laser interferometry of colliding plasmas," SPIE conference on Soft X-ray lasers and Applications, San Diego, August 2005; Proc. SPIE Int. Soc. Opt. Eng. 5919, (2005).
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